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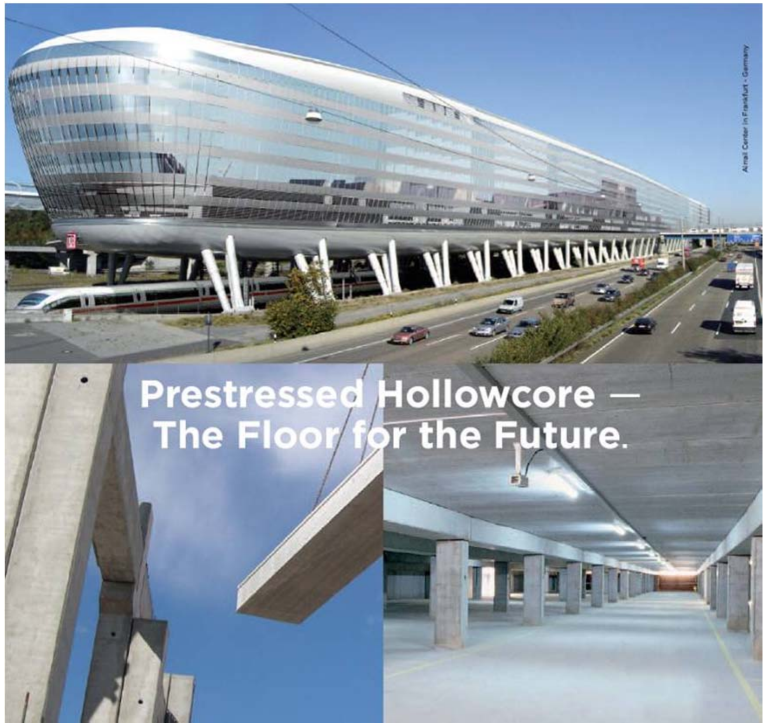
INTERNATIONAL PRESTRESSED HOLLOWCORE ASSOCIATION

Spalling in EN1168



Technical Seminar
October 26th and 27th 2011
RWTH-IMB Aachen (GE)

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1. Bursting, spalling and splitting: what's the difference?

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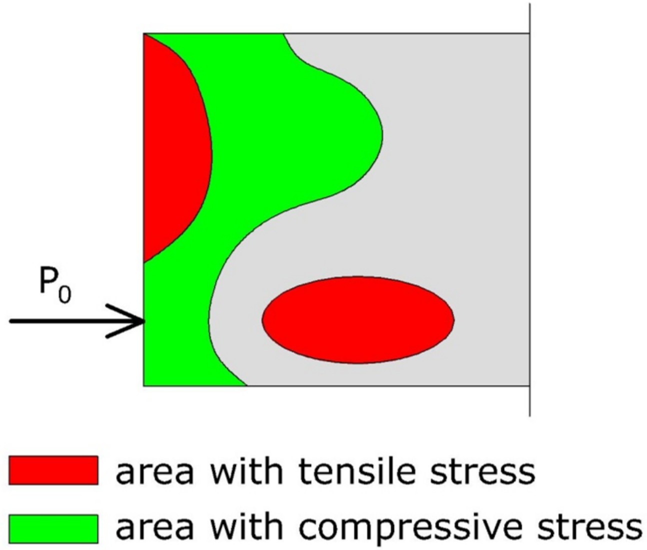
- **Introduction**
  - Transfer of prestress force to the concrete is locally, with high stress concentrations.
  - Principle of Jean Claude Barré de Saint-Venant → prestress force spreads out into a linear stress distribution (anchorage zone).
  - Nonlinear stress distribution in this zone.
  - Complex stress state:
    - High compressive stresses just after the loading point.
    - High tensile stresses perpendicular to the line of action of the force (bursting and spalling).



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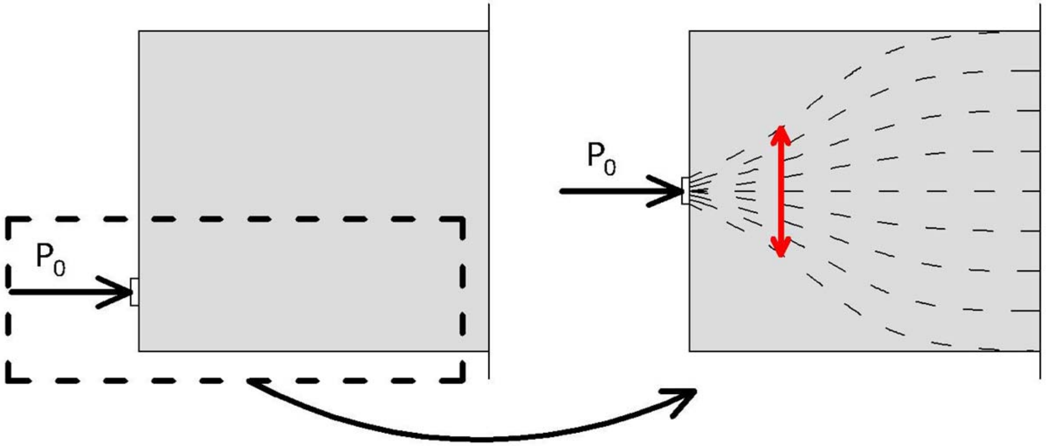
1. Bursting, spalling and splitting: what's the difference?

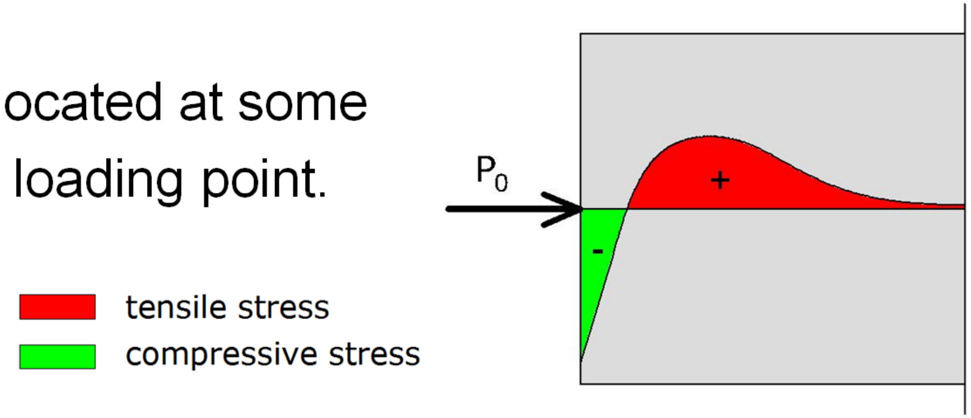
- **Bursting**
  - Spreading of the prestress force causes curved compressive stress trajectories wich generates transverse tensile stresses (bursting stresses).



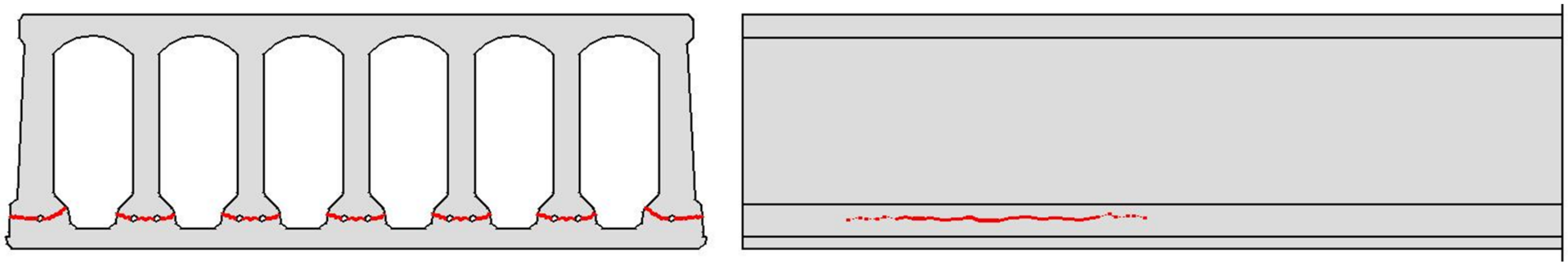
  - Bursting stresses occur along the line of action of the prestress force.

1. Bursting, spalling and splitting: what's the difference?

- **Bursting**
  - Maximum stress is located at some distance behind the loading point.

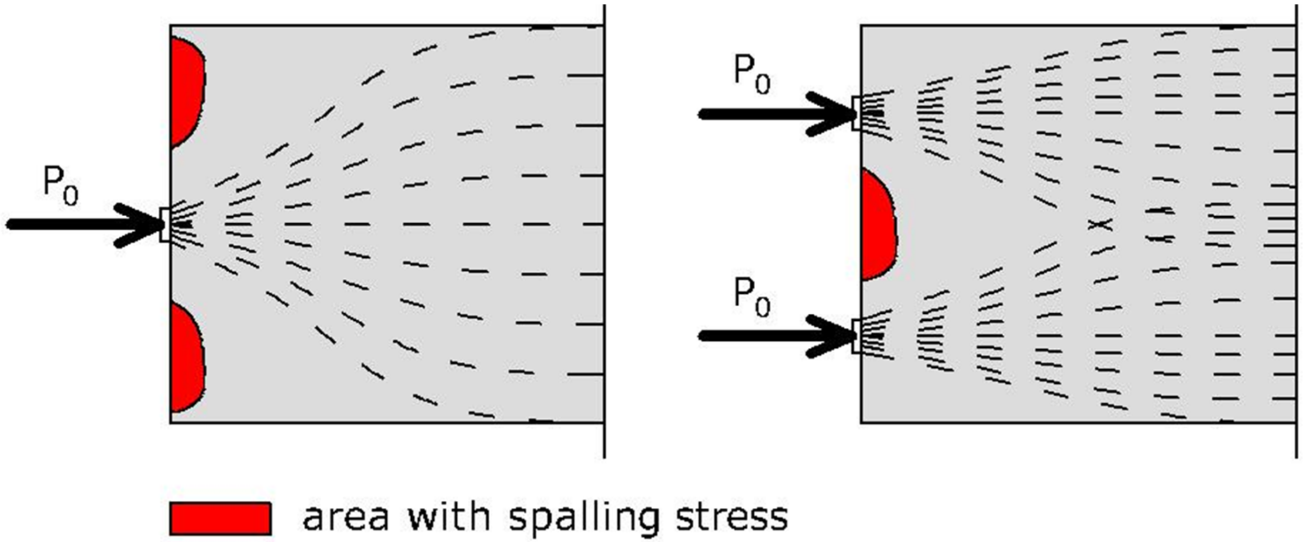


  - Possible crack pattern (at release and its growth afterwards):



1. Bursting, spalling and splitting: what's the difference?

- **Spalling**
  - Prestress force leads to compressive stress trajectories.
  - Parts of the concrete are not subjected to pressure.
  - Stress discontinuity between the compressed and non compressed zones results in shear and tensile stresses.



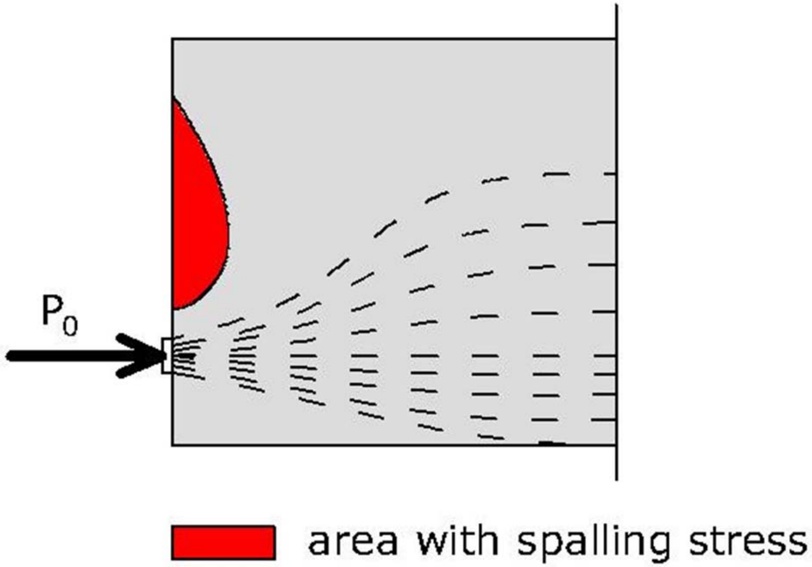
1. Bursting, spalling and splitting: what's the difference?

- **Spalling**
  - Eccentric prestress: the eccentricity will cause extra curving of the already curved compressive stress trajectories.

    → Area with spalling stresses is bigger.

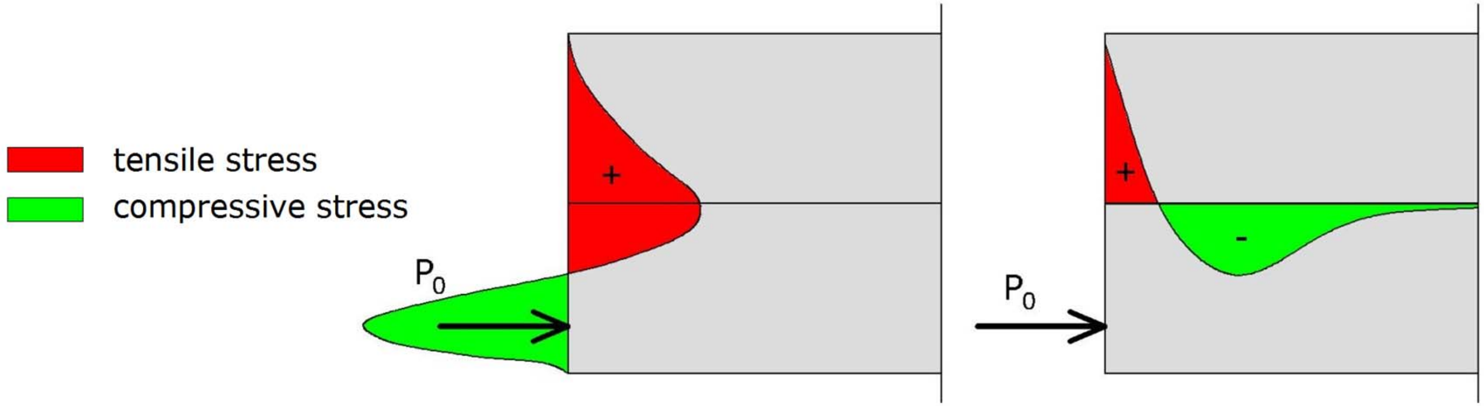
    → Max. spalling stress is bigger.

  - Spalling stresses develop beside the loading point along the border of the member .

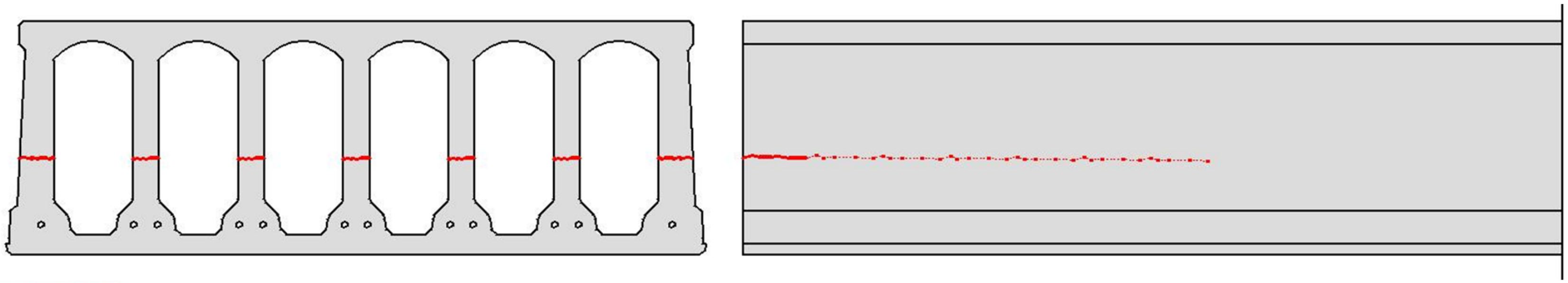


1. Bursting, spalling and splitting: what's the difference?

- **Spalling**
  - Maximum stress is located about mid hight at member end.



  - Possible crack pattern (at release and its growth afterwards):



1. Bursting, spalling and splitting: what's the difference?

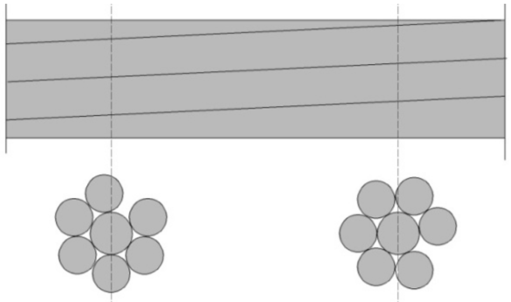
- **Spalling**

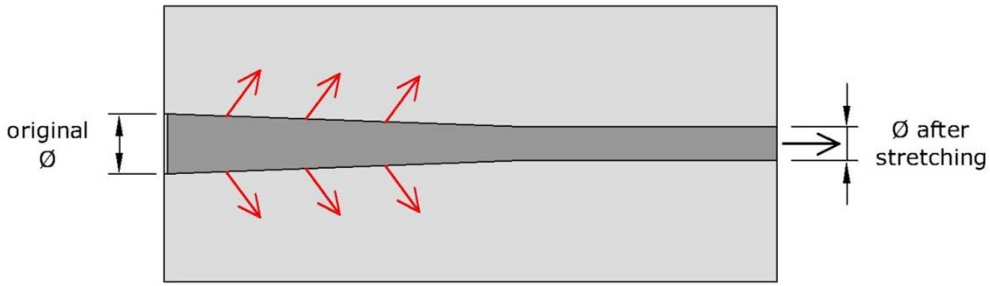
Crack opening
is large !

Crack length
is large !

1. Bursting, spalling and splitting: what's the difference?

- **Splitting**
  - Only in case of prestressing (prestress transfer bond).
  - Stresses occur locally around the tendons.
  - Radial compressive stresses due to, such as :
    - Loose cement paste particles get stuck (failure adhesion)
    - Hoyer effect
    - Lack of fit

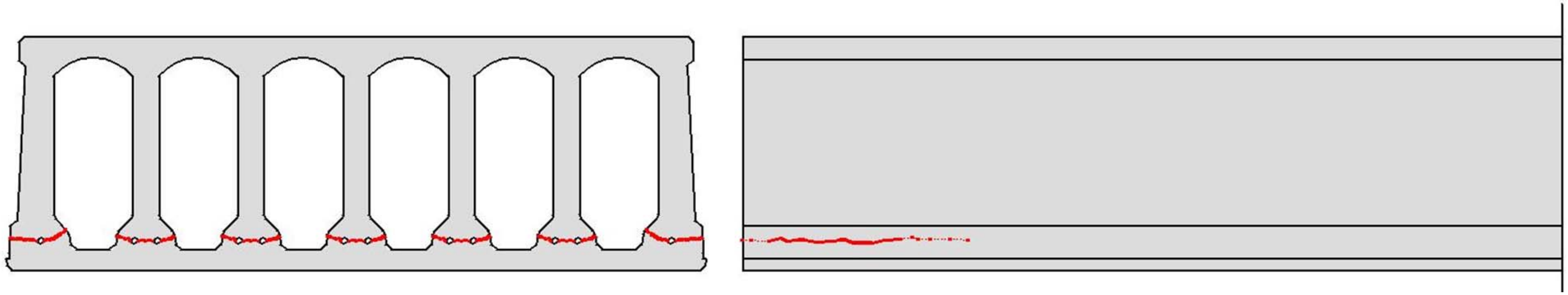




→ circumferential tensile stresses

1. Bursting, spalling and splitting: what's the difference?

- **Splitting**
  - Maximum stress is located in the beginning of the transmission zone (original diameter of prestressing steel).
  - Possible crack pattern (at release and its growth afterwards):



  - Splitting cracks and bursting cracks are difficult to distinguish.

1. Bursting, spalling and splitting: what's the difference?

- **How to check bursting, spalling and splitting in the design of the slab?**
  - Bursting + splitting:

    Art. 4.3.1.2.2 EN1168: 'Minimum concrete cover and axis distances of prestressing steel'.

    → c_{min} to the nearest concrete surface and to the nearest edge of a core.

    → independent of the magnitude of the prestressing (in France 'chemins de fendage')
  - Spalling:

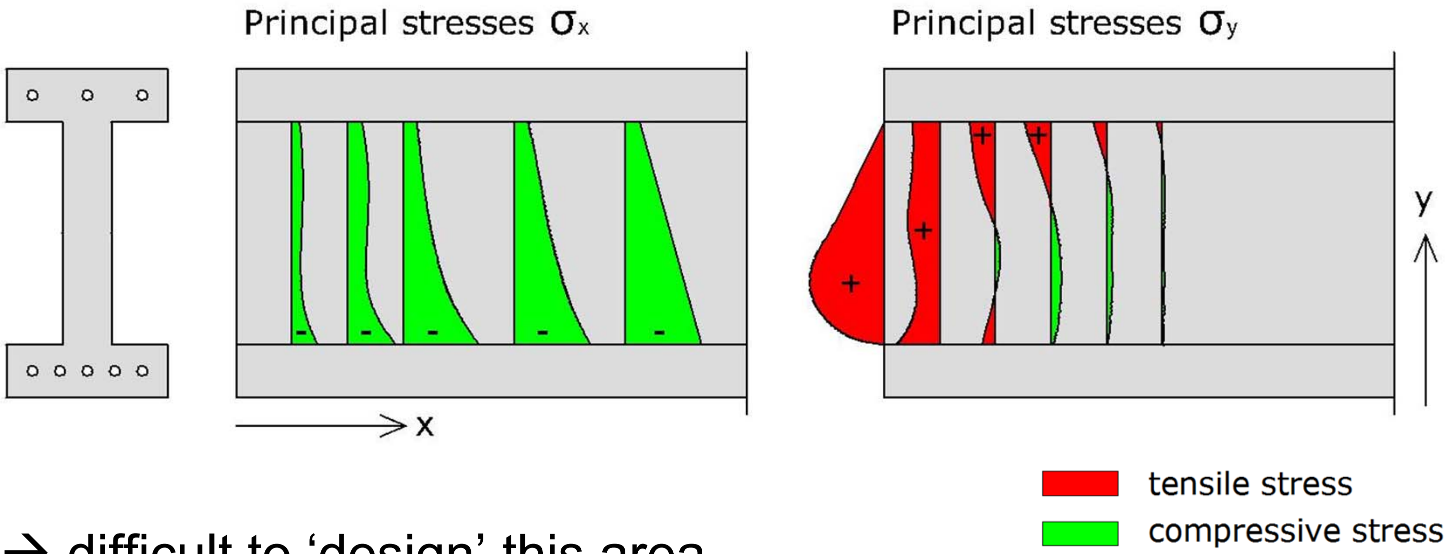
    Art. 4.3.3.2.1 EN1168: 'Resistance to spalling for prestressed hollow core slabs'.

    → formula max. stress → chapter 3 of this presentation.

2. Calculation maximum spalling stress

2. Calculation maximum spalling stress

- **Introduction**
  - Nonlinear distribution of longitudinal stress σ_x in the sections of the 'disturbed' anchorage zone → Navier-Bernoulli hypothesis (plane sections remain plane after bending) is not valid.
  - Nonlinear distribution of transverse stress σ_y.
  - E.g. web I-beam:

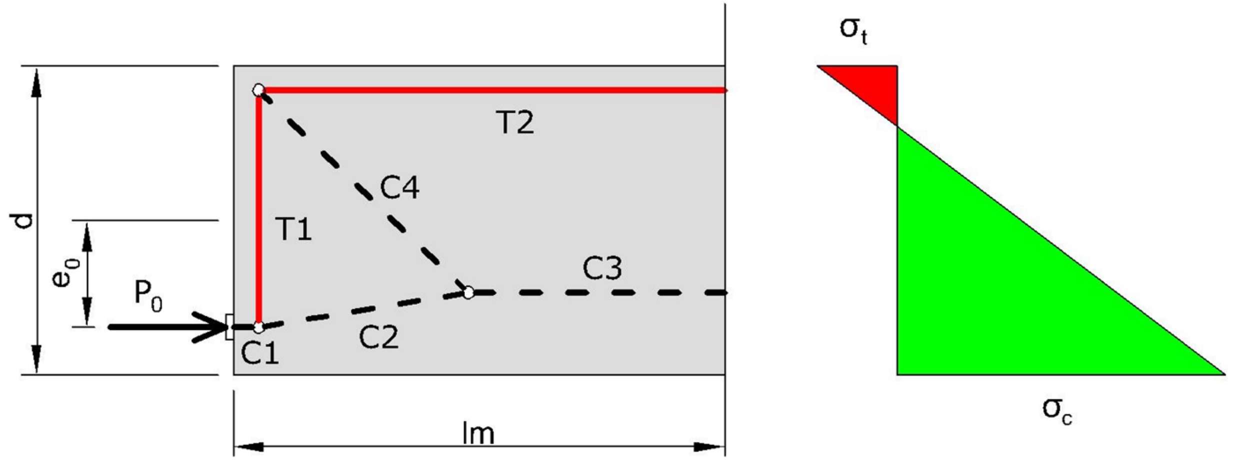


→ difficult to 'design' this area.

2. Calculation maximum spalling stress

- **Second half 20th century**
  - A lot of research on the tensile stresses in the transmission zone.
  - In the USA and Europe.
  - Mostly post-tensioning (higher stress concentration).
  - Impossible to present a complete overview.
- **Simple cross sections**
  - Strut-and-Tie Model: useful in locating zones of concrete tensile and compressive stress.

    E.g. Truss analogy of Mörsch:



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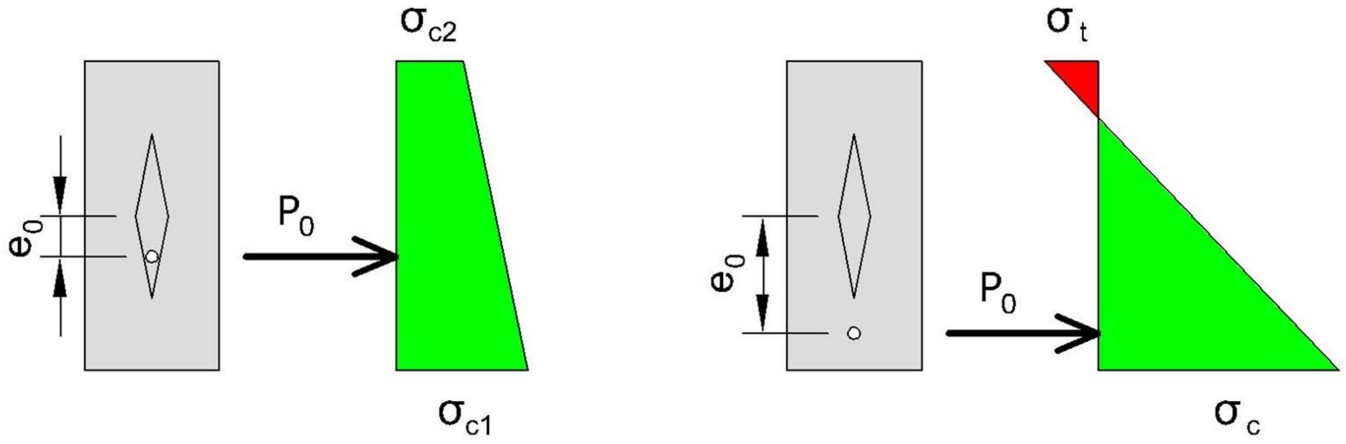
2. Calculation maximum spalling stress

- **Simple cross sections**
  - Strut-and-Tie Model:

Max. stress rectangular cross section :

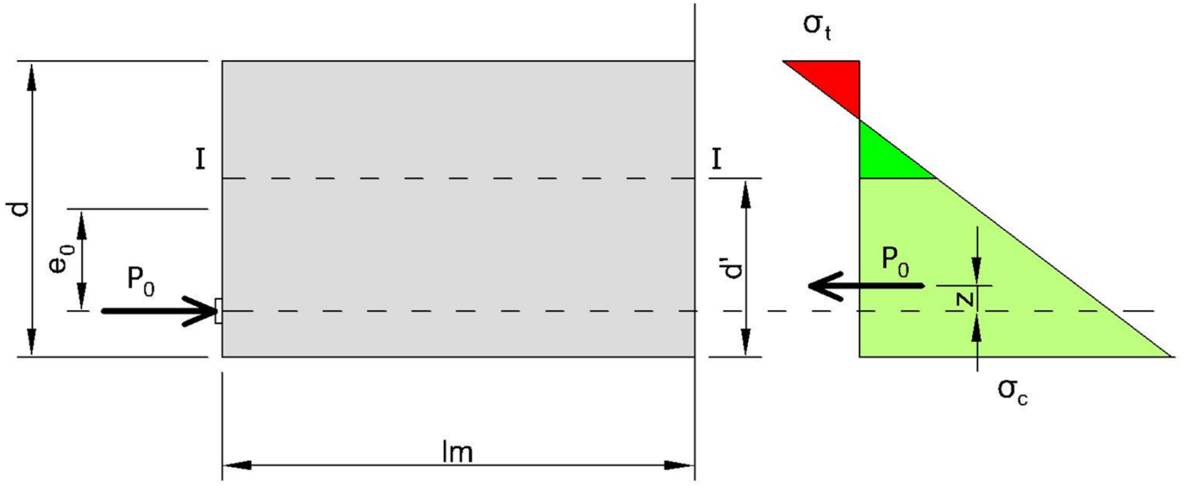
$$\sigma_{sp} = \frac{16.\left(\frac{e_0}{d} - \frac{1}{6}\right)^2}{e_0 . l_m^{\ 2}} . \frac{P_0 . d^2}{b}$$

This formula works if P_0 acts outside the core of the cross section.



2. Calculation maximum spalling stress

- **Simple cross sections**
  - Kupfer's method = equivalent prism analogy → equilibrium of a part of the transmission zone.



d' is chosen so that the resultant of the stresses acting at the transmission zone end is equal to the prestressing force.

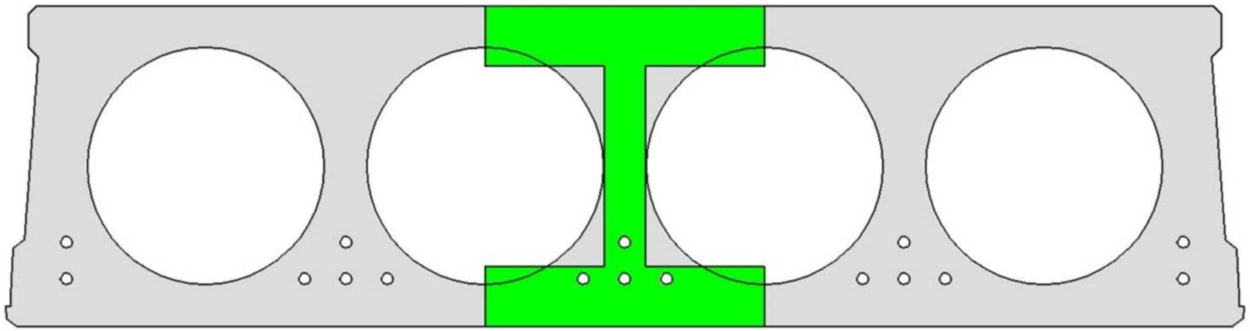
Max. stress rectangular cross section :

$$\sigma_{sp} = \frac{8.P_0.\left(\frac{d^2}{6.e_0} - \frac{d}{108.e_0^{\ 2}} - d + 2.e_0\right)}{l_m^{\ 2}.b}$$

→ CEB-FIB Model Code 1990

2. Calculation maximum spalling stress

- **Cross section hollow core slabs**
  - Not a simple cross section.
  - Prestressing force is not distributed uniformly across the width of the slab.
  - Transformation to simple cross sections (equivalent I-section).



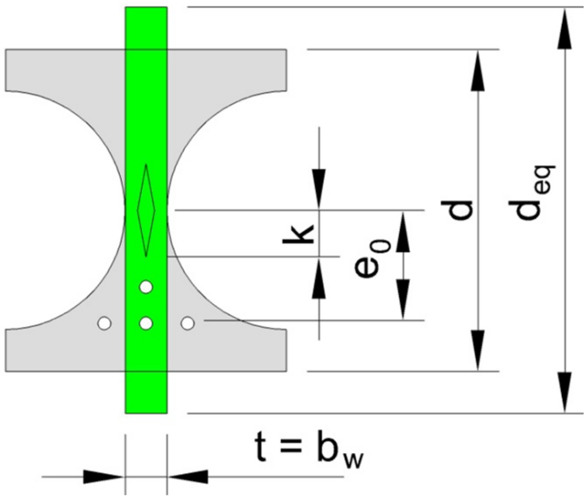
Same area and moment of inertia

→ Calculate the max. spalling stress with the discussed methods.

2. Calculation maximum spalling stress

- **Cross section hollow core slabs**
  - Transformation to simple cross sections (equivalent rectangular section).

    FEA of J.A. den Uijl (TU Delft) showed that the spalling stress of a rectangular section and a I-section are the same, as long as the relative eccentricity and the web width are the same.



$$d_{eq} = \frac{e_0}{\frac{(e_0 - k)}{d} + \frac{1}{6}}$$

$$\frac{e_0 - k}{d} = \text{relative eccentricity}$$

$$k = \text{core radius of cross section}$$

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2. Calculation maximum spalling stress

- **Cross section hollow core slabs**
  - Finite element analysis
    - Analytical assessment of the spalling stresses is only approximately possible.
    - To get a better understanding about:
      - The influence of some parameters on magnitude;
      - Distribution of the stresses;

    J.A. den Uijl performed finite element analysis.

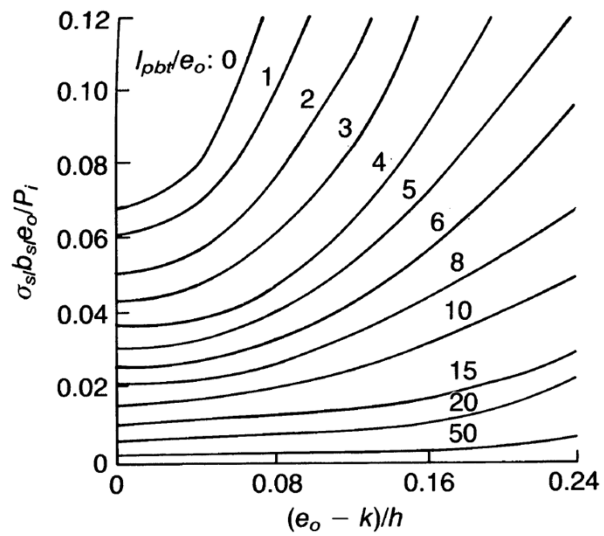
$$\sigma_{sp} = \frac{P_0}{b_w . e_0} . \frac{2.\left(0{,}02 + 4.\alpha_e^{\;2{,}3}\right).\left(\alpha_e + \frac{1}{6}\right)}{\left(0{,}1 + 0{,}5.\alpha_e\right).\left(1 + 1{,}5.\left(\frac{l_t}{e_0}\right)^{1{,}5} . \left(\alpha_e + \frac{1}{6}\right)^{1{,}5}\right)} = \text{max. stress}$$

$$with \quad \alpha_e = \frac{e_0 - k}{d} = \text{relative eccentricity} \quad \& \quad l_t = \text{transmission length}$$

2. Calculation maximum spalling stress

- **Cross section hollow core slabs**
  - Den Uijl's formula of σ_{sp}:
    - → Web or whole section.
    - → $\sigma_{sp} \leq f_{ctkj}$ = characteristic tensile strength at prestressing
    - → Only for members with d < 400 mm.
    - → Influence of upper reinforcement was not analyzed.
    - → FIP recommendations 'Precast prestressed hollow core floors' (Thomas Telford, London, 1988).

      $\sigma_{sp} \leq f_{ctkj}$
    - → CEB-FIB Model Code 1990 + 2010 (graph).



$$1990: \sigma_{sp} \leq \frac{f_{ct,fl}}{\gamma_c} \text{ with } f_{ct,fl} = \text{mean flexural tensile strength } \& \ \gamma_c = 1{,}5$$

$$2010: \sigma_{sp} \leq f_{ctd} = \frac{f_{ctk}}{\gamma_c} = \text{design concrete tensile strength}$$

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3. Spalling stress according EN1168

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3. Spalling stress according EN1168

- for each web or for the whole section (strands/wires well distributed over the width of the element):

$$\sigma_{sp} = \frac{P_0}{b_w.e_0} . \frac{15.\alpha_e^{2,3} + 0,07}{1 + \left(\frac{l_{pt1}}{e_0}\right)^{1,5} .(1,3.\alpha_e + 0,1)} = \text{max. stress}$$

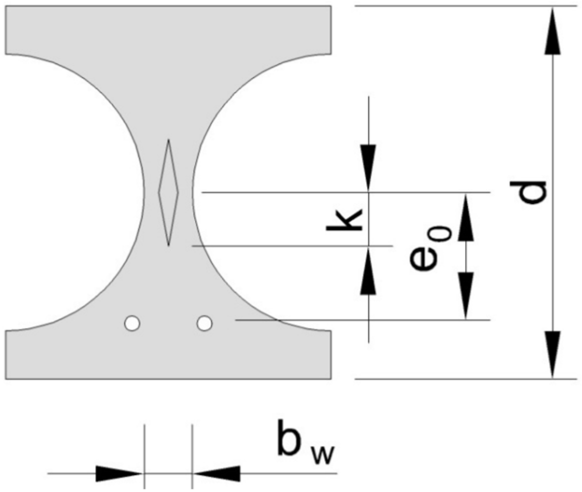
$$with \quad \alpha_e = \frac{e_0 - k}{d} = \text{relative eccentricity} \geq 0$$

$$k = \frac{W_b}{A_c} = \text{core radius}$$

$$\mathrm{W_b} = \text{section modulus bottom fibre}$$

$$\mathrm{A_c} = \text{area of cross section}$$

$$l_{pt1} = \text{lower desing value of transmission length}$$



3. Spalling stress according EN1168

- Similarity with formula of J.A. den Uijl:

$$\sigma_{sp} = \frac{P_0}{b_w.e_0}.\frac{2.\left(0{,}02+4.\alpha_e^{\,2{,}3}\right).\left(\alpha_e+\frac{1}{6}\right)}{\left(0{,}1+0{,}5.\alpha_e\right).\left(1+1{,}5.\left(\frac{l_t}{e_0}\right)^{1{,}5}.\left(\alpha_e+\frac{1}{6}\right)^{1{,}5}\right)}$$

Rewritten with almost equal σ_{sp} as result (if $l_t = l_{pt1}$).

$$\sigma_{sp} = \frac{P_0}{b_w.e_0}.\frac{15.\alpha_e^{\,2{,}3}+0{,}07}{1+\left(\frac{l_{pt1}}{e_0}\right)^{1{,}5}.\left(1{,}3.\alpha_e+0{,}1\right)}$$

More background information on this transformation is welcome.

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3. Spalling stress according EN1168

- Use the formula OR fracture-mechanics design shall prove that spalling cracks will not develop : study of the propagation of cracks using the method of finite elements.

- Visible horizontal spalling cracks in the webs are not allowed !

- Value of transmission length?
  - Calculated according EN1992-1-1 → rather high values.
  - Experimental research → up to 50% less!
  - Important parameter !

3. Spalling stress according EN1168

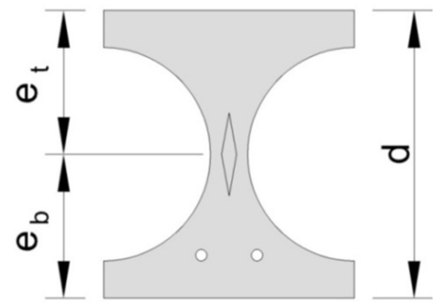
- Relative eccentricity ≥ 0:

$$\text{P}_0 \text{ in core} \rightarrow e_0 < k \rightarrow \alpha_e = \frac{e_0 - k}{d} < 0 \rightarrow \alpha_e = 0$$

$$\rightarrow \sigma_{sp} = \frac{P_0}{b_w.e_0} \cdot \frac{0{,}07}{1 + \left(\frac{l_{pt1}}{e_0}\right)^{1{,}5} .0{,}1}$$

- Section modulus : Bottom fibre or top fibre?

$$W_b = \frac{I}{e_b} \quad \text{or} \quad W_t = \frac{I}{e_t} = \frac{I}{d - e_b} ?$$



3. Spalling stress according EN1168

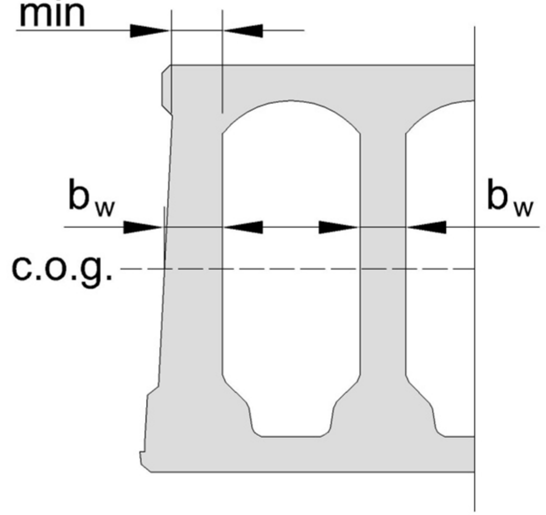
- Section modulus : got lost in translation?

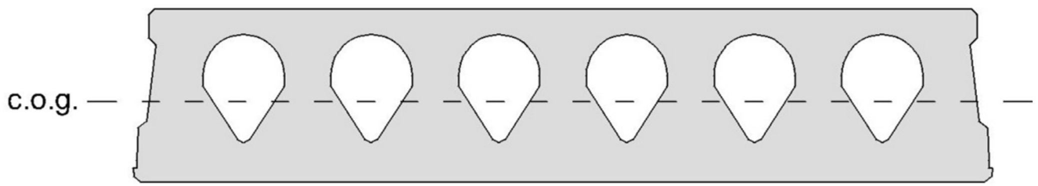
$$W_b = \frac{I}{e_b} \qquad \& \qquad W_t = \frac{I}{e_t} = \frac{I}{d - e_b}$$

σ_{sp} for upper reinforcement (max. tensile in bottom fibre)

σ_{sp} for lower reinforcement (max. tensile in top fibre)

- Thickness of the web b_w:
  - The minimum thickness?
  - Better to use thickness at center of gravity?





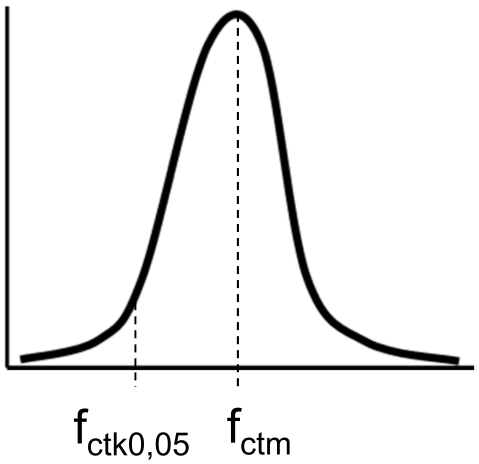
3. Spalling stress according EN1168

- $\sigma_{sp} \leq f_{ct}$ = tensile strength at release on the basis of tests.
  - Potential vs. structural strength (overestimating of strength).

    Need for a method to measure the structural tensile strength in a simple and quick way !

    → Research topic?

  - Characteristic value vs. mean value.



f_{ctm} = mean

→ 50 % is smaller !

→ used in the evaluation of a specific case

$f_{ctk0,05}$ = 5% fractile

→ only 5 % is smaller

→ used in the design of the slab

3. Spalling stress according EN1168

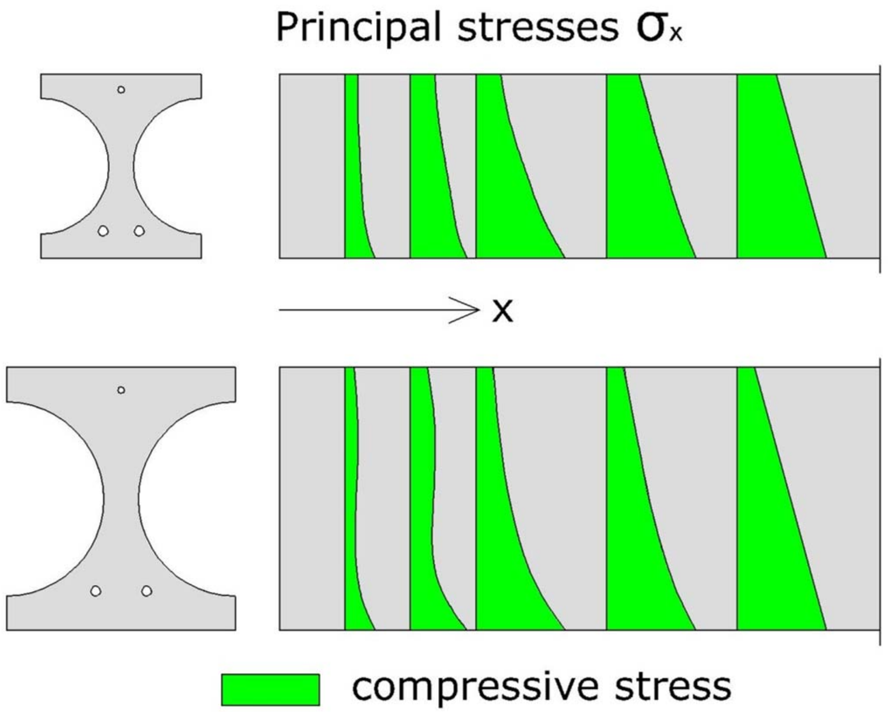
- $\sigma_{sp} \leq f_{ct}$ = tensile strength at release on the basis of tests.
  - Points of interest:
    - You don't know how far it is until cracking, but all slabs are subjected to a test during first lifting from the production bed.

      → stresses due to lifting or suspension must be added to become a 'safer' situation?
    - Spalling cracks can occur shortly (1-2 days) after production, due to the short-term creep of concrete.
    - Increasing the compressive strength of the concrete at release of prestress works at 'both sides':
      - Higher tensile strength.
      - Higher spalling stress, due to the shorter transmission length.

$$\uparrow \sigma_{sp} \leq f_{ct} \uparrow$$

3. Spalling stress according EN1168

- How to deal with members with d ≥ 400 mm?
  - FEA in the past: d < 400 mm.
  - Is the formula valid for d ≥ 400 mm?
    In thick members the stress distribution in the sections of the anchorage zone will be 'more' nonlinear than in thin members.



3. Spalling stress according EN1168

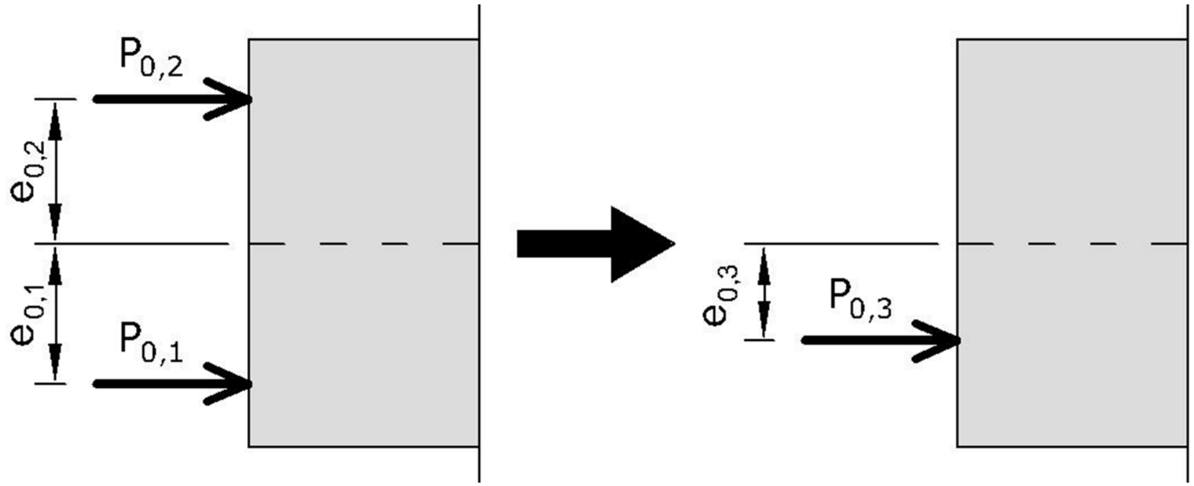
- How to deal with members with d ≥ 400 mm?
  - Scope of EN1168:
    - prEN 1168: 1997: maximum d = 440 mm
    - EN 1168: 2005 + A2(2009): maximum d = 500 mm

      → formula of σ_{sp} validated with experimental research?

  - More en more thicker hollow core slabs are used:
    - d = 450, 500, 800, ….. 1000 mm: search the limit of application of our products
    - In practice a high risk on spalling
    - Competitor of double T floor

3. Spalling stress according EN1168

- How to deal with upper reinforcement?
  - FEA in the past: only with lower reinforcement.
  - 1st way to use the formula?
    - Replace prestress force + eccentricity of the upper and lower reinforcement by one prestress force + eccentricity and then calculate σ_{sp}?



Statically equivalent systems, but different σ_{sp} because local effects are different (principle of Saint-Venant).

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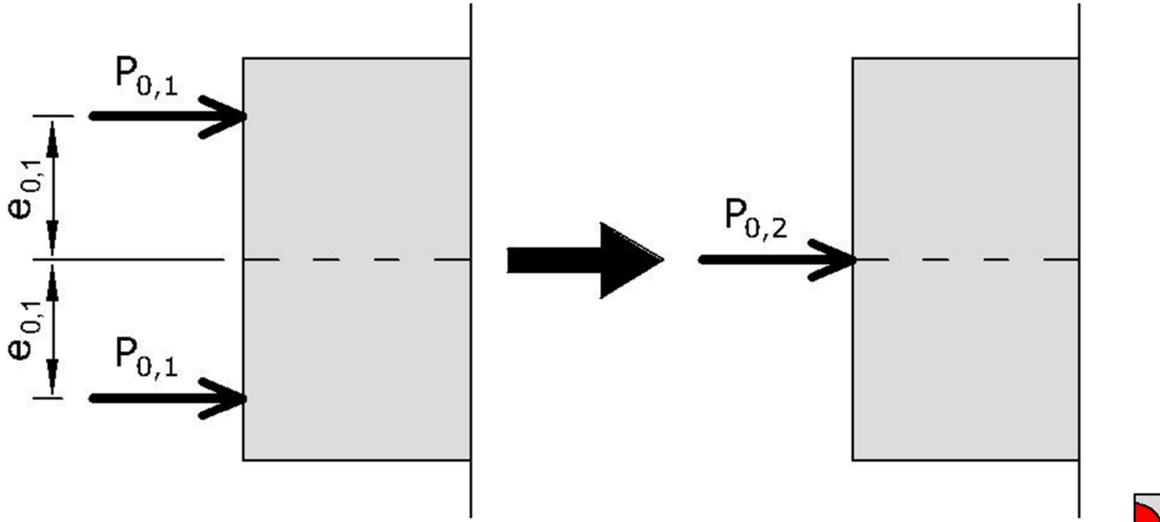
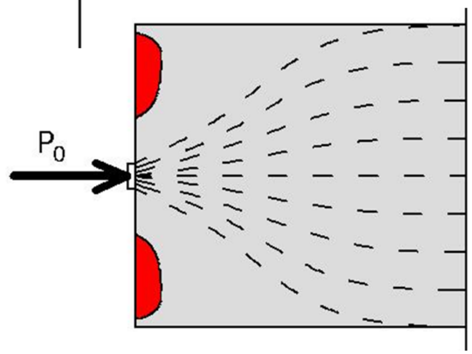
3. Spalling stress according EN1168

- How to deal with upper reinforcement?
  - 1st way to use the formula?
    - What in case of 2 symmetric forces (e.g. wall elements)?

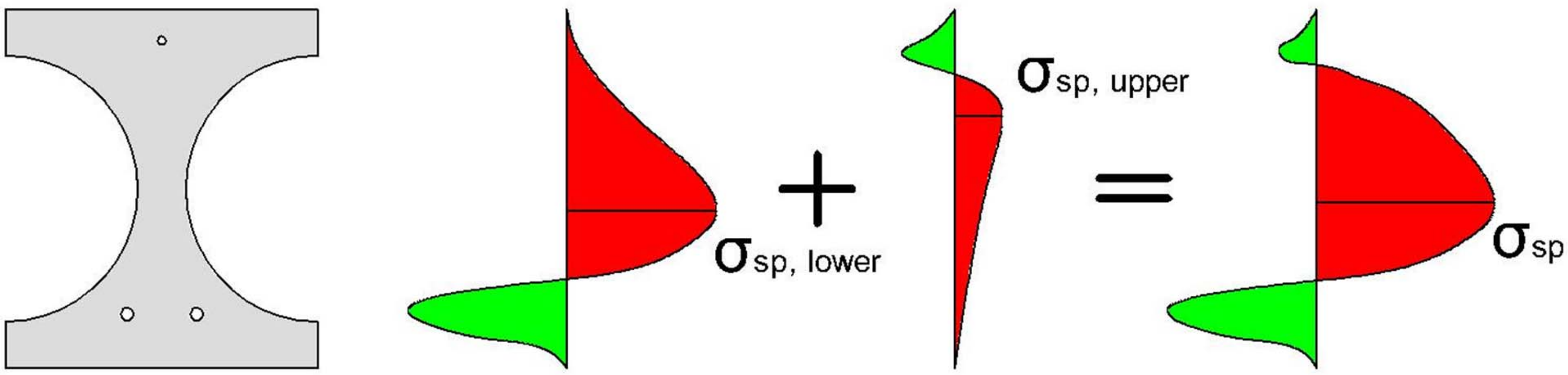


Statically equivalent systems, but different σ_{sp} because local effects are different.
EN1168 → $e_{0,3} = 0$ → σ_{sp} = #DIV/0!



3. Spalling stress according EN1168

- How to deal with upper reinforcement?
  - 2^{nd} way to use the formula?
    - Calculate σ_{sp} lower reinforcement → $\sigma_{sp,\ lower}$
      Calculate σ_{sp} upper reinforcement → $\sigma_{sp,\ upper}$
      $\sigma_{sp,\ lower}$ and $\sigma_{sp,\ upper}$ are located at different hights.



$\sigma_{sp,\ lower} + \sigma_{sp,\ upper}$ is not correct.

3. Spalling stress according EN1168

- How to deal with upper reinforcement?
  - 3th way to use the formula?
    - Just ignore σ_{sp} of the upper reinforcement.

      → probably done the most, but the negative effect is ignored!

  - Positive impact of the upper reinforcement in case of thin slabs? Negative impact in case of thick slabs?

    What's a thin or a thick slab in this sense?

  - Upper reinforcement in hollow core slabs is used:
    - In some seismic areas (e.g. New Zealand)
    - When handling is a problem
    - In wall panels (d is rather limited; +/- 200 mm)

4. Conclusion

4. Conclusion

- For d < 400 mm and without upper reinforcement the formula of EN1168 works fine.

- Further research is needed to find a more ‘correct/reliable’ method for calculating the maximum spalling stress in hollow core slabs with d ≥ 400 mm and/or upper reinforcement.

  On behalf of ECHO, a theoretical study was started by two students of Xios Hogeschool Limburg in Hasselt, Belgium :

  - Building of a finite element model for slabs with and without upper reinforcement;
  - Formulate a truss analogy (strut-and-tie model);
  - Work out a generally valid formula (d < 400 mm and d ≥ 400 mm).

4. Conclusion

- Ideal would be to perform an experimental research to validate the results of the theoretical study:
  - Very expensive !
  - Share practical experience of manufacturers → ‘sharepoint’ on the internet in the future?

- The design regarding spalling should be always a ‘bottom up design’ = some slabs that fails in the model, will satisfy in practice.

- Products evolve, standards should do too!

Thank you for your attention!

Questions?

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